New Gas Gun Helping Scientists Better Understand Plutonium Behavior

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ONE of the most daunting scientific and engineering challenges today is ensuring the safety and reliability of the nation's nuclear arsenal. To effectively meet that challenge, scientists need better data showing how plutonium, a key component of nuclear warheads, behaves under extreme pressures and temperatures. On July 8, 2003, Lawrence Livermore researchers performed the inaugural experiment of a 30-meter-long, two-stage gas gun designed to obtain those data. The results from a continuing stream of successful experiments on the gas gun are strengthening scientists' ability to ensure that the nation's nuclear stockpile is safe and reliable.

The JASPER (Joint Actinide Shock Physics Experimental Research) Facility at the Department of Energy's (DOE's) Nevada Test Site (NTS) is home to the two-stage gas gun. In the gun's first test, an unqualified success, Livermore scientists fired a projectile weighing 28.6 grams and traveling about 5.21 kilometers per second when it impacted an extremely small (about 30-gram) plutonium target. This experiment marked the culmination of years of effort in facility construction, gun installation, system integration, design reviews, and federal authorizations required to bring the experimental facility online.

Ongoing experiments have drawn enthusiastic praise from throughout DOE, the National Nuclear Security Administration (NNSA), and the scientific community. NNSA Administrator Linton Brooks said, "Our national laboratories now have at their disposal a valuable asset that enhances our due diligence to certify the nuclear weapons stockpile in the absence of underground nuclear weapons testing."

Bruce Goodwin, associate director of Livermore's Defense and Nuclear Technologies Directorate, said, "I am proud of the team effort that has produced the successful JASPER shots. I have personal appreciation for the extraordinarily challenging nature of plutonium. The precise data generated by these gas-gun experiments will open up our scientific understanding of plutonium."

Mark Martinez, Livermore's JASPER test director, notes that the experimental results have been so good they are generating significant interest in accelerating the test schedule. "The JASPER data are demonstrating superb quality and indicate that JASPER will meet its intended goal of generating high-precision plutonium data," he says.

JASPER was built at a total cost of about $20 million and sited in existing aboveground buildings at NTS. The facility was developed by personnel from Lawrence Livermore, Los Alamos, and Sandia

The JASPER Facility is located at the Department of Energy's Nevada Test Site, about 105 kilometers northwest of Las Vegas. The facility is housed in three buildings previously used to support Los Alamos National Laboratory's nuclear test program.

national laboratories and Bechtel Nevada, the NTS prime contractor.

Gas Guns Well Established

A well-established experimental technique for determining the properties of materials at high pressures, temperatures, and strain rates is to use a gas gun to shock a small sample of material with a projectile traveling at high velocity and then diagnose the material's response. Lawrence Livermore's three two-stage gas guns have made important contributions to solving scientific puzzles in condensed-matter physics, geophysics, and planetary science. For example, in 1996, Livermore's largest two-stage gas gun produced metallic hydrogen for the first time. Recently, with experimental techniques that will be used at JASPER, this gas gun was also used to determine the melting point of iron at Earth's core.

Neil Holmes, chief JASPER scientist and head of Livermore's shock physics program, says that two advantages of a gas gun are its proven dependability and scientists' extensive experience with it. Lawrence Livermore has more than 40 years experience shocking materials with gas guns. "When the projectile hits the target, the pressure wave is as steady as it can be," says Holmes. "As a result, researchers can focus on the target and diagnostics rather than the gun's performance."

Scientists fire projectiles from the JASPER gas gun into plutonium targets equipped with instruments for measuring and recording data. The projectile's impact produces a shock wave that passes through the target in a millionth of a second or less, creating pressures of more than 600 gigapascals (6 million times the pressure of air at Earth's surface), temperatures to thousands of kelvins, and densities several times that of plutonium's original solid state.

The JASPER team's role in the Stockpile Stewardship Program is to measure the fundamental properties of plutonium. Data from the experiments are used to determine material equations of state, which express the relationship between pressure, density, and temperature. The equation of state is essential for generating reliable computational models of plutonium's behavior under weapons-related conditions. Knowledge of these properties is required to assess, without nuclear testing, the performance, safety, and reliability of nuclear weapons.

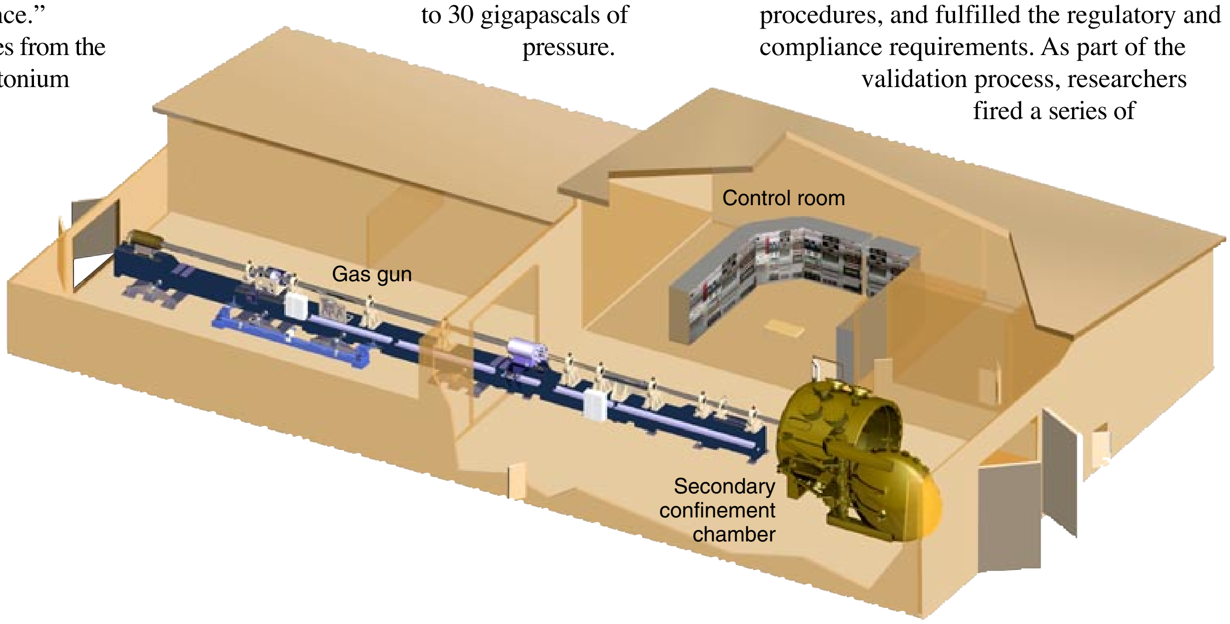
Long Qualification Phase

Prior to the construction of JASPER, the only facility available for performing shock tests on plutonium was the 40-millimeter, single-stage gas gun built at Livermore and currently located at Los Alamos. This gun can achieve a maximum projectile velocity of about 2 kilometers per second and up to 30 gigapascals of pressure.

Researchers determined that much higher projectile velocities were needed to achieve the desired conditions for plutonium research. Two-stage, light gas guns similar to the JASPER gun have been operational at Lawrence Livermore, Los Alamos, and Sandia national laboratories for many years, but they are not licensed to perform experiments on plutonium.

In the late 1990s, it was recognized that a new two-stage gas-gun facility dedicated to plutonium research, and located in a remote location, could provide valuable data on plutonium's equations of state. Ideally, the facility would operate with a short turnaround time between shots and at a modest cost per shot. In early 1998, a study conducted by a team of scientists and engineers from several national laboratories identified the Able Site at NTS as the best location. The site's three main buildings had previously been used by Los Alamos's nuclear test program.

Construction and facility modifications at the Able Site started in April 1999 and were completed in September 1999. The JASPER gas gun was installed in early 2000, and the first system-integration demonstrations were completed in September 2000. From February 2001 to April 2003, Livermore staff verified the gun performance and containment systems, validated the diagnostics and operating procedures, and fulfilled the regulatory and compliance requirements. As part of the validation process, researchers fired a series of



JASPER's two-stage gas gun, seen in this artist's depiction, measures 30 meters long and includes a secondary confinement chamber that encloses the primary target chamber.

20 shots using nonnuclear materials to qualify the gun for use with nuclear materials. At the conclusion of the installation project, JASPER managers received NNSA Defense Programs Excellence and DOE Project Management awards.

Livermore operates the facility for NNSA, and Bechtel Nevada supplies resources for facility maintenance and operation, and diagnostic design and operation.

JASPER Gun Matches Livermore's

The JASPER gas gun was designed to match the internal dimensions of the large two-stage gas gun at Livermore, which has been operational since 1972. By copying that design, researchers took advantage of the extensive database and experience that exists from using the Livermore gun, thereby minimizing the effort required to characterize the JASPER gun at start-up. Although the internal dimensions are the same, JASPER's containment system is significantly more complex because the Laboratory's gas gun is not used with hazardous materials such as plutonium and, hence, does not require a special material-confinement system. (See the box on p. 8.) The Livermore gas gun serves as a test bed for developing techniques and training personnel for future experiments at JASPER. "We work out JASPER experiments first on our two-stage gun at Livermore with nonnuclear materials," says Martinez.

JASPER's gas gun is driven first with gunpowder and then with a light gas. In the first stage, hot gases from the gunpowder propellant drive a 4.5-kilogram plastic deformable piston down a pump tube. The piston compresses a light gas, typically hydrogen, as it travels down the narrowing tube. This gas, which is the second-stage driving medium, is compressed until it builds up enough pressure to burst a valve. The explosive gas accelerates a 15- to 30-gram projectile down the launch tube toward the target at a velocity of up to 8 kilometers per second. (See the figure on p. 9.)

The projectile is made of plastic with a flat, metal plate embedded in its face to directly impact the plutonium target. Depending on the desired shock pressure, the metal plate is made of aluminum, tantalum, or copper. A typical projectile measures 28 millimeters in diameter and weighs 25 grams.

The speeding projectile enters the primary target chamber (PTC), which houses the plutonium target. Just prior to entering the PTC, the passing projectile is sensed by a continuous x-ray source and detector, which trips a switch that triggers the detonation of the ultrafast closure valve. This valve effectively traps radioactive debris within the PTC following the projectile's impact on the plutonium target.

The two-stage gas gun at the JASPER Facility in Nevada fired its first shot in July 2003. Livermore operates the facility for the National Nuclear Security Administration. Bechtel Nevada supplies resources for facility maintenance and operation, and diagnostic design and operation.

Electronics project engineer John Warhus monitors preparations for a gas-gun experiment from the JASPER control room.

When the projectile hits the plutonium target, the impact produces a high-pressure shock wave of about 600 gigapascals. The temperature, a critical variable in a material's equation of state, can reach as high as 7,000 kelvins. By comparison, the surface of the Sun is about 5,800 kelvins. The destroyed plutonium target is contained within the PTC. Following the experiment, the PTC is discarded and sent to the federal Waste Isolation Pilot Plant in New Mexico.

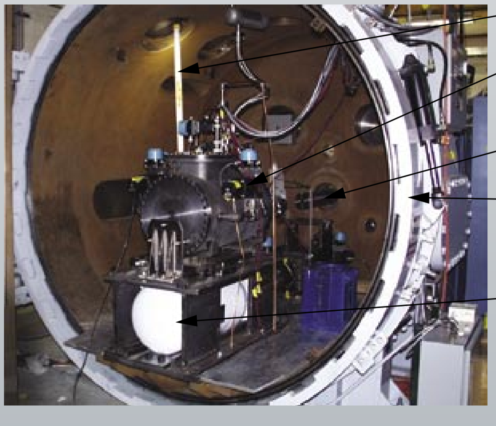
Projectile velocities are precisely determined by experimental parameters such as the type and amount of gunpowder, the driving gas, the diameter of the barrel, and the mass of the projectile. JASPER facility manager Ben Garcia notes that as a precaution, all shots are first simulated using gun performance codes on computers. "We want to make sure we don't produce any pressures that could exceed the design limits of the gun," he says.

Currently, the major diagnostic instruments are two flash x-ray units, which measure projectile velocity to within 0.1 percent accuracy, and electrical pins, which measure the speed of the shock wave from the impact of the projectile. The facility also has the capability to use a Velocity Interferometer System for Any Reflector (VISAR), a tool that measures the velocity of the exploding target by recording Doppler-shifted reflected light.

Confining Plutonium Is Central to JASPER Gas-Gun Design

Livermore engineers adopted a dual-layered approach for JASPER's two-stage gas gun to ensure that plutonium dust or fragments are not released into the building or the environment after each experiment. The two layers are the primary target chamber (PTC) and the secondary confinement chamber. The PTC, which houses the plutonium target, is designed to contain target material under worst-case conditions following impact with the speeding projectile. The PTC is discarded after every shot and shipped to the federal Waste Isolation Pilot Plant in New Mexico.

Lead PTC engineer Matt Cowan notes that designing the PTC has been a challenge because of the dynamic loading of the PTC during a shot. "We anticipated two potential failure modes in the PTC: loads that cause a rupture in the pressure vessel and loads that cause a dynamic gap at the sealing surfaces."



The primary target chamber, which houses the plutonium target, is designed to contain target material under worst-case conditions. It is located inside the secondary confinement chamber. Other key features inside the secondary confinement chamber include the flash x ray for measuring projectile velocity, the continuous x ray for tripping the ultrafast closure valve, and the high-explosive gas accumulator for trapping gases after the ultrafast closure valve has been tripped.

The engineers conducted extensive modeling to determine where plutonium debris would be distributed inside the PTC following impact with a projectile. In addition, experiments using plutonium surrogates provided valuable experience in refining the design of the PTC. For example, researchers applied a layer of phosphorous-32, which has a two-week half-life, to a gold target because radioactive materials are easier to detect if they escape from the PTC. Debris shields were added to absorb some of the momentum of high-velocity impacts and to protect critical O-rings that seal the PTC's interior. "JASPER experiments cause particulates to fly everywhere at extremely high speeds, so we need to protect O-rings from the sandblasting effect," explains Cowan. Engineers also expanded the volume of space around the target impact plane.

Livermore's High Explosives Applications Facility (HEAF) was used to demonstrate the PTC's design limits. The testing at HEAF created explosive forces about 150 percent of the predicted dynamic loads that the PTC would experience with plutonium targets. The data from HEAF agreed with results from simulations and strengthened the engineers' confidence that plutonium would be contained.

The PTC's ultrafast closure-valve system at the chamber's entrance was designed and manufactured by Ktech Inc. (Albuquerque, New Mexico), and adapted for use on JASPER by Livermore engineers. The valve closes a 1.3-centimeter-diameter aluminum tube in about 60 microseconds by detonating 90 grams of high explosives wrapped around the tube. The valve then traps plutonium debris within the PTC. "A splash-back of plutonium travels at the same speed as the projectile, so we need to close the tube extremely quickly," says Cowan.

The PTC is located in the secondary confinement chamber, which has a large circular door to access the PTC. The secondary chamber ensures that any material that might escape from the PTC will not migrate into the building. "The secondary chamber is not expended after a test," says Cowan, "and it is not significantly challenged during a shot."

As a final precaution, radiation-control technicians, fully suited with respirators and radiation detectors, enter the gas-gun building following every shot to make sure the plutonium debris has been fully contained within the PTC.

These data are essential to understanding plutonium's material properties. Additional diagnostic instruments are planned that will measure the temperature, electrical conductivity, and other characteristics of the target after impact.

Targets Made at Livermore

The first series of JASPER experiments used plutonium targets nicknamed "top hats," which consist of a plutonium disk the size of a half dollar bonded to a smaller, nickel-size disk of plutonium. The top hat design was first proven on Livermore's two-stage gas gun with copper, aluminum, and tantalum disks.

Engineer Randy Thomas, who is responsible for the production and machining of JASPER targets at Livermore, notes the top hat targets must meet extremely precise requirements: flat to within 2.5-millionths of a meter with the two faces of each disk parallel to each other within 2.5-millionths of a meter. Meeting such tight tolerances requires a complex and time-consuming production and machining process. Plutonium is first cast into a cylinder using a graphite mold. The resulting cylinder is sliced into disks and then heated to eliminate internal stress. The disks are rolled with specific orientations to obtain correct metallurgical properties, heated again, and machined until they are within less than 1 percent of their final dimensions. Then the disks are checked for the correct density and radiographed to detect any voids and inclusions. Even slight imperfections result in the plutonium target being unusable. The disks undergo final machining and inspection to ensure they are flat and parallel. Then they are bonded together.

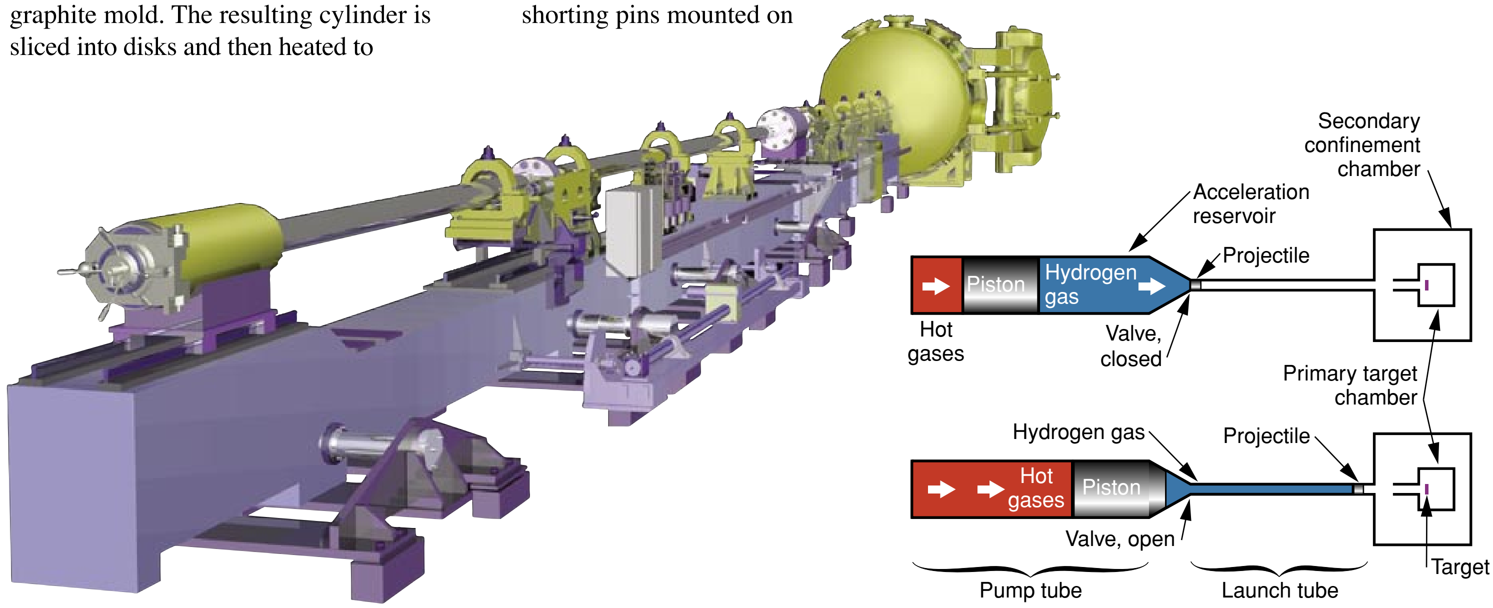
After final measurement and characterization, the plutonium is loaded into the target assembly. The assembly is aligned beforehand so that the projectile will impact the target at its exact center. The target assembly is leak tested, backfilled with an inert atmosphere, placed in a federally approved shipping container, and trucked to NTS. Holmes describes the final product as, "The highest quality plutonium samples we've ever seen. That quality reflects the superb plutonium fabrication and machining capabilities at Livermore."

The top hat plutonium target uses 13 diagnostic electrical-shorting pins mounted on its surface: 6 on the large disk, 6 on the small disk, and 1 that fits through a hole in the middle of the smaller disk. On impact from the projectile, a shock wave travels through the base plate and electrically shorts the pins. The velocity of the shock front passing through the target is calculated using the measured shock arrival times from the shorting pins and the known target thickness. The pins' orientations allow for correcting the effects of projectile tilt during target impact.

Data for Equations of State

Livermore scientists are excited about the experimental results. "The JASPER gas gun has validated itself as an important tool for plutonium shock physics. Everything has worked as planned," says Holmes. "We're thrilled with the quality of data. These experiments have never before been done on plutonium with this accuracy."

Each JASPER experiment provides one data point on plutonium's Hugoniot curve. The Hugoniot is derived from conservation of mass, momentum, and energy equations using experimental values of projectile



A schematic showing how a two-stage gas gun operates. In the first stage, hot gases from the powder propellant drive a piston, which compresses the hydrogen gas in the pump tube. In the second stage, the high-pressure gas ruptures the valve, accelerating the projectile down the launch tube toward the target.

velocity (flash x-ray data) and shock velocity (electrical pin data). Hugoniot curves are then used to develop material equation-of-state models used in weapon performance calculations.

"Equation of state is one of the most important elements in building a robust capability for predicting weapon performance," says Holmes. "We mainly use theoretical equations of state for our simulations. That's not sufficiently accurate for stockpile stewardship purposes. We need data that will either validate our theories or force changes in them."

JASPER experiments complement the subcritical nuclear materials experiments that Livermore scientists have conducted underground at NTS since 1997. (See *S&TR,* July/August 2000, pp. 4–11.) Those experiments use high explosives to blow apart tiny amounts of plutonium but stop short of nuclear chain reactions. These complex hydrodynamic experiments provide vital information on the behavior and performance of aging nuclear materials.

The gas gun allows scientists to study plutonium over a broader range of conditions than is the case with subcritical experiments. Moreover, gas-gun technology eliminates uncertainties introduced by high-explosive-driven experiments. Holmes points out that gas-gun experiments can generate distortions in projectiles, but the distortions are always the same shape and are readily accounted for.

Future Directions

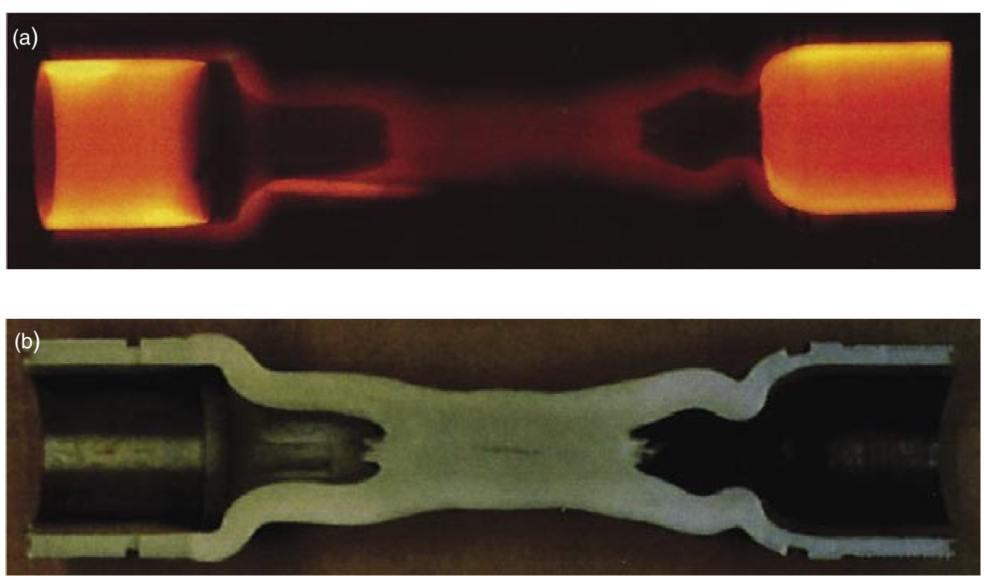
The early experimental successes have generated significant discussion regarding how to schedule more experiments and how to extract more data from each experiment.

To meet the increasing demand for experiments, the JASPER team is exploring ways to increase the number of experiments scheduled from the current 12 per year. For example, a glove box (required for safe handling of plutonium) has been commissioned at the Device Assembly Facility (DAF) at NTS, located about 15 kilometers from JASPER. Livermore managers are planning to ship plutonium samples from Livermore to DAF for final bonding and placement in the target assembly to support a busier schedule. Using DAF would also decrease the risk of damage from transporting finished plutonium targets and diagnostics over a long distance.

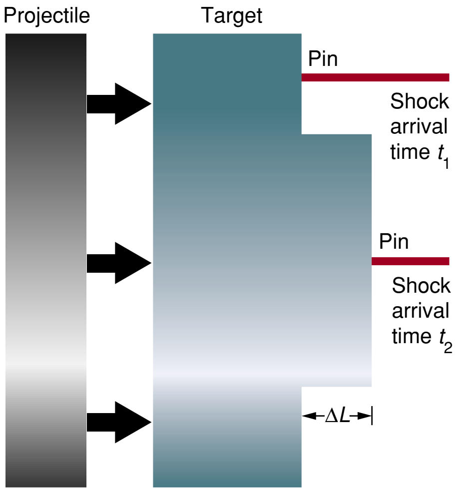
New diagnostics are being considered to generate additional information about the physical processes occurring in shocked plutonium. For example, plans are under way to measure electrical and thermal conductivity as well as sound speeds of shocked plutonium targets. The optical properties of the shocked target—the light emitted during an experiment—will also be studied using lasers.

Another set of experiments being planned would test aged plutonium to determine if its shocked properties are different from newly cast material. At the same time, physicists and engineers are looking at new projectile designs, such as those made of different densities, to

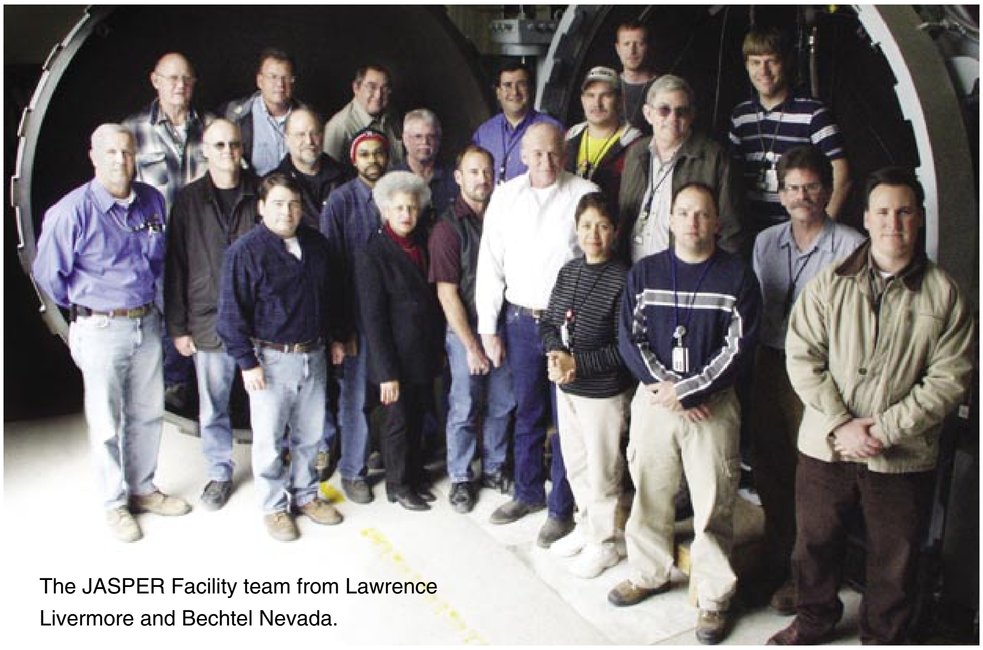
An extrudable piston is shown before and after firing. The piston compresses hydrogen gas in the first stage of the two-stage gas gun.



(a) An x ray and (b) a photograph show the ultrafast closure valve after it detonates to prevent any plutonium debris from escaping from the primary target chamber.



Electrical pins on the target measure the velocity of the shock front as it passes through the target material. Velocity is determined by dividing the difference in pin position (ΔL) by the difference in shock arrival time ($t_1 - t_2$).



The JASPER Facility team from Lawrence Livermore and Bechtel Nevada.

obtain specific shock pressures. Martinez recalls how Livermore personnel once predicted, "If we build it (JASPER), they will come." He notes that physicists at Los Alamos are designing a series of experiments, as are colleagues from Britain's Atomic Weapons Establishment. In fact, about 10 years of shots are already in the planning stages. Martinez says, "People are getting new ideas all the time to find out more about plutonium with JASPER."

—*Arnie Heller*

Key Words: Device Assembly Facility, equation of state, gas gun, Hugoniot curve, Joint Actinide Shock Physics Experimental Research (JASPER) Facility, Nevada Test Site (NTS), plutonium, stockpile stewardship, Velocity Interferometer System for Any Reflector (VISAR).

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JASPER Update

Fifteen successful shots were fired with the JASPER two-stage gas gun at the Nevada Test Site (NTS) in 2004. An experiment on December 14 was the eighth plutonium shot for the year, the eleventh plutonium experiment in the series, and the thirty-eighth shot since the gas gun became operational in March 2001. For the December 14 shot, the JASPER team used a bullet to create the first isentropic compression on a plutonium sample. The method used a new Livermore-developed impactor technology, allowing the JASPER team to investigate plutonium at pressures and densities previously inaccessible to experimentalists.

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